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6. AUTHORS
I. Chuang

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Massachusetts Institute of Technology (MIT)
Office of Sponsored Programs
Bldg. E19-750
Cambridge, MA 02139 -4307

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14. ABSTRACT
Trapped ion systems, are extremely promising for large-scale quantum computation, but face a vexing problem, with motional quantum states decohering as trap sizes are reduced, far more rapidly than expected due to Johnson noise. This heating issue leads to low quantum logic gate fidelities. Furthermore, integration with fiber optic and CMOS control technologies introduces new materials, typically dielectrics and semiconductors, known to cause high heating when positioned too close to ions. This project developed and deployed a unique cryogenic ion trap

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Report Title

Comprehensive Materials and Morphologies Study of Ion Traps (COMMIT) for scalable Quantum Computation - Final Report

ABSTRACT

Trapped ion systems, are extremely promising for large-scale quantum computation, but face a vexing problem, with motional quantum states decohering as trap sizes are reduced, far more rapidly than expected due to Johnson noise. This heating issue leads to low quantum logic gate fidelities. Furthermore, integration with fiber optic and CMOS control technologies introduces new materials, typically dielectrics and semiconductors, known to cause high heating when positioned too close to ions. This project developed and deployed a unique cryogenic ion trap system for fast test & evaluation of ion heating rates, characterizing surface-electrode ion traps made of copper, gold, silver, aluminum, nickel, niobium, and niobium nitride traps. These trap materials were fabricated using a wide variety of techniques, including e-beam deposition, electroplating, and sputtering. And traps were operated under a wide range of conditions, including temperatures varying from 6K to room temperature. Measurements of the superconducting traps indicate that noise sources are likely on the surface, instead of being due to sub-surface defects. Overall, results show a significant reduction of heating rates, by up to three orders of magnitude, for certain materials, when operated at 6K, versus at room-temperature. This offers a promising direction for advancing large-scale fault-tolerant quantum computation with microfabricated ion trap systems.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/04/19 2: 7	Peter F. Herskind, Isaac L. Chuang, Tony Hyun Kim. Surface-electrode ion trap with integrated light source, Applied Physics Letters, (05 2011): 0. doi: 10.1063/1.3593496
2012/04/19 2: 6	Tony Kim, Peter Herskind, Taehyun Kim, Jungsang Kim, Isaac Chuang. Surface-electrode point Paul trap, Physical Review A, (10 2010): 0. doi: 10.1103/PhysRevA.82.043412
2012/04/19 2: 2	Isaac Chuang, Shannon Wang, Jaroslaw Labaziewicz, Yufei Ge, Ruth Shewmon. Demonstration of a quantum logic gate in a cryogenic surface-electrode ion trap, Physical Review A, (06 2010): 0. doi: 10.1103/PhysRevA.81.062332
2012/04/19 2: 4	Peter F. Herskind, Shannon X. Wang, Molu Shi, Yufei Ge, Marko Cetina, Isaac L. Chuang. Microfabricated surface ion trap on a high-finesse optical mirror, Optics Letters, (08 2011): 0. doi: 10.1364/OL.36.003045
2012/04/19 2: 5	Shannon X. Wang, Guang Hao Low, Nathan S. Lachenmyer, Yufei Ge, Peter F. Herskind, Isaac L. Chuang. Laser-induced charging of microfabricated ion traps, Journal of Applied Physics, (11 2011): 0. doi: 10.1063/1.3662118
2012/04/19 2: 3	Shannon X. Wang, Yufei Ge, Jaroslaw Labaziewicz, Eric Dauler, Karl Berggren, Isaac L. Chuang. Superconducting microfabricated ion traps, Applied Physics Letters, (12 2010): 0. doi: 10.1063/1.3526733
2012/04/19 2: 1	D. Schuster, G. M. Akselrod, P. B. Antohi, J. Labaziewicz, Y. Ge, Z. Lin, W. S. Bakr, I. L. Chuang. Cryogenic ion trapping systems with surface-electrode traps, Review of Scientific Instruments, (01 2009): 0. doi: 10.1063/1.3058605

TOTAL: 7

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
2012/04/21 1' 8	D.R. Leibrandt, J. Labaziewicz, R.J. Clark, I.L. Chuang, R.J. Epstein, C. Ospelkaus, J.H. Wesenberg, J.J. Bollinger, D. Leibfried, D.J. Wineland, D. Stick, J. Sterk, C. Monroe, C.-S. Pai, Y. Low, R. Frahm, R.E. Slusher. DEMONSTRATION OF A SCALABLE, MULTIPLEXED ION TRAPFOR QUANTUM INFORMATION PROCESSING, Quantum Information and Computation (07 2009)

TOTAL: 1

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Chuang - elected Fellow of the American Physical Society in 2010

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Shannon Wang	0.50	
Yufei Ge	0.75	
Jaroslaw Labaziewicz	0.50	
Paul Antohi	0.25	
David Leibrandt	0.50	
Tony Kim	0.50	
Robert Clark	0.25	
FTE Equivalent:	**3.25**	
Total Number:	**7**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Peter Herskind	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Isaac Chuang	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Ruth Shewmon	0.50	EECS
Nathan Lachenmyer	0.50	Physics
Tony Kim	0.00	EECS
Tongyan Lin	0.25	Physics
FTE Equivalent:	**1.25**	
Total Number:	**4**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	4.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:	4.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:	4.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	4.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	3.00

Names of Personnel receiving masters degrees

NAME
Tony Kim

Total Number: **1**

Names of personnel receiving PHDs

NAME
Robert Clark
Jaroslaw Labaziewicz
David Leibrandt
Paul Antohi

Total Number: **4**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

Comprehensive Materials and Morphologies study of Ion Traps (COMMIT) for scalable quantum computation

Final Report

ARO Project W911NF-07-R-0003

April, 2012

EXECUTIVE SUMMARY

Trapped ion systems, are extremely promising for large-scale quantum computation, but face a vexing problem, with motional quantum states decohering as trap sizes are reduced, far more rapidly than expected due to Johnson noise. This heating issue leads to low quantum logic gate fidelities. Furthermore, integration with fiber optic and CMOS control technologies introduces new materials, typically dielectrics and semiconductors, known to cause high heating when positioned too close to ions. This project developed and deployed a unique cryogenic ion trap system for fast test & evaluation of ion heating rates, characterizing surface-electrode ion traps made of copper, gold, silver, aluminum, nickel, niobium, and niobium nitride traps. These trap materials were fabricated using a wide variety of techniques, including e-beam deposition, electroplating, and sputtering. And traps were operated under a wide range of conditions, including temperatures varying from 6K to room temperature. Results show a significant reduction of heating rates, by up to three orders of magnitude, for certain materials, when operated at 6K, versus at room-temperature. This offers a promising direction for advancing large-scale fault-tolerant quantum computation with microfabricated ion trap systems.

Principal Investigator:

Prof. Isaac Chuang
MIT EECS & Department of Physics
32 Vassar St., 26-251
Cambridge, MA 02139
Tel: (617) 253-1692
E-mail: ichuang@mit.edu

Administrative Point of Contact:

Mary McGonagle
MIT
Office of Sponsored Programs
77 Massachusetts Ave, E19-750
Cambridge, MA 02139-4307
tel: 617-258-8017
fax: 617-253-4734

1 Final Report

1.1 Stataement of problem and approach

Trapped ion systems are a leading technology for realizing large-scale quantum computers, particularly because of the integrability of chip-based ion traps, which leverage substantial semiconductor lithography and atomic physics capabilities. A significant challenge which must be overcome, however, is the fact that the motional quantum state of trapped ions have been found to decohere extremely rapidly as trap sizes are reduced. Typical ion heating rates, of above ~ 1000 quanta per second in current ~ 50 micrometer scale traps[SCR+06], extrapolate to 10^7 quanta per second heating at the 10 micrometer trap size goal of the community[Ste07]. Unfortunately, such high heating leads to controlled-NOT gate error rates several orders of magnitude higher than allowed for fault-tolerance.

Due to this heating issue, a significant challenge also arises in development of trap designs and materials suitable for technology integration. A working computing system will require substantial integrated optics for delivery of laser beams for cooling, measurement, and gates, as well as control electronics for moving ions and feedback control of events. The materials used in these elements must be compatible with the ion trap, but it is known that surface charges on nearby dielectrics and semiconductors can lead to high ion heating rates.

Where do the anomalously high ion heating rates come from, and how can they be reduced enough to allow fault-tolerant quantum computation with highly integrated trapped ion systems?

Traditional ion trap experiments have been slow to provide ion heating measurements, due to the hand-crafted nature of three-dimensional traps, and the long cycle time required for room-temperature UHV systems. Significant advances were made with the introduction of surface-electrode ion traps[CBB+05], which allow bulk microfabrication, and with the introduction of a cryogenic needle ion trap, which used liquid nitrogen to enable operation at 150 Kelvin[DOS+06]. However, cycle times for experiments have still remained long, with typical two-week bakeout periods necessary, and trap fabrication lead times of weeks to months.

This project utilizes a system and methodology for fast-cycle test & evaluation of ion trap materials and morphologies, and their impact on ion heating rates[LGA+]. Extending prior art in the field[PBIW96, OWN+02, WL95], we mount a surface electrode ion trap on the 4K baseplate of a liquid helium bath cryostat. This enables UHV to be reached from STP in less than 12 hours; measurements indicate an oxygen partial pressure of better than 10^{-14} torr under our operating conditions. In addition, we designed and implemented a set of four optical feedback stabilized external cavity diode lasers[LRB+07], and a sophisticated FPGA based feedback control system, which enables quick and reliable sideband cooling of individual strontium ions.

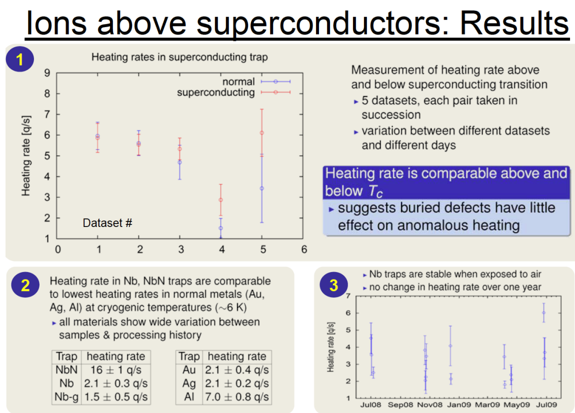
This new fast-cycle test & evaluation capability makes possible, for the first time, a comprehensive study of the dependence of ion heating rates on trap materials and morphologies. Our project performed such a comprehensive study, with the goals of (1) reducing heating rate to acceptable levels for fault-tolerant two-qubit gates, (2) identifying compatible materials for integration with optical and control technologies, and (3) understanding the ultimate origin of ion heating. The study evaluated material systems for both the electrode and substrate of surface-electrode traps, as well as materials needed for integration with control circuit and fiber delivery technologies. Models for heating mechanisms were also developed.

2 Summary of most important results

Five main results of this project are:

1. Ion heating is most likely coming from surface adsorbates or surface physics, and very unlikely to be arising from sub-surface defects, due to the lack of difference in ion heating rates above superconducting traps, measured below and above the superconducting transition temperature.

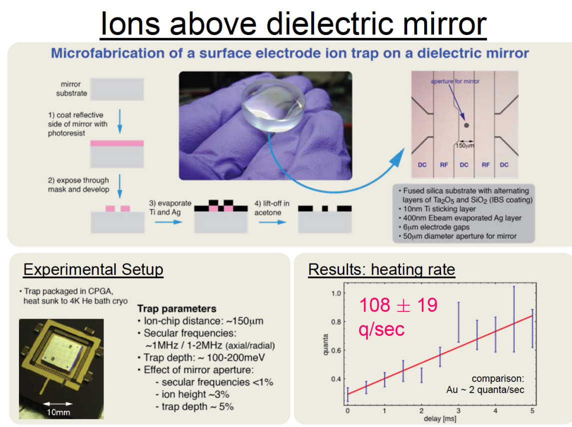
   Publication: Shannon X. Wang, Jaroslaw Labaziewicz, Yufei Ge, Ruth Shewmon, and Isaac L. Chuang Demonstration of a quantum logic gate in a cryogenic surface-electrode ion trap Phys. Rev. A, vol. 81, 062332 (2010) [WGL+10]



   We fabricate superconducting ion traps with niobium and niobium nitride and trap single 88Sr ions at cryogenic temperatures. The superconducting transition is verified and characterized by measuring the resistance and critical current using a four-wire measurement on the trap structure, and observing change in the rf reflection. The lowest observed heating rate is 2.1(3) quanta/s at 800 kHz at 6 K and shows no significant change across the superconducting transition, suggesting that anomalous heating is primarily caused by noise sources on the surface. This demonstration of superconducting ion traps opens up possibilities for integrating trapped ions and molecular ions with superconducting devices.We fabricate superconducting ion traps with niobium and niobium nitride and trap single 88Sr ions at cryogenic temperatures. The superconducting transition is verified and characterized by measuring the resistance and critical current using a four-wire measurement on the trap structure, and observing change in the rf reflection. The lowest observed heating rate is 2.1(3) quanta/s at 800 kHz at 6 K and shows no significant change across the superconducting transition, suggesting that anomalous heating is primarily caused by noise sources on the surface. This demonstration of superconducting ion traps opens up possibilities for integrating trapped ions and molecular ions with superconducting devices.

2. Ions traps can be fabricated above high-finesse optical mirrors without significantly degrading the mirror quality.

   Publication: Peter F. Herskind, Shannon X. Wang, Molu Shi, Yufei Ge, Marko Cetina, and Isaac L. Chuang Microfabricated surface ion trap on a high-finesse optical mirror Opt. Lett. 36, 3045-3047 (2011)[HWS+11]

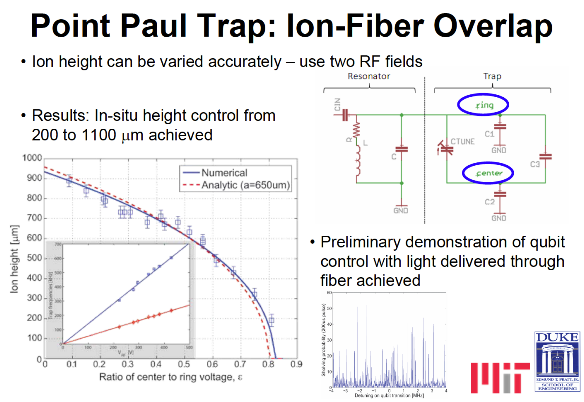


Integration of optics with single atomic particles is of considerable interest in the exploration of the basic quantum physics of atom-light interactions as well as for the advancement of quantum information science and cavity quantum-electrodynamics (CQED). Much progress has been made in integrating mirrors, lenses, and optical fibers within hundreds of micrometers from neutral atoms and trapped ions. High-finesse optical cavities around ions have also been investigated, but thus far, only with relatively large, millimeter-scale distances between ions and mirror surfaces. Integration of smaller cavities is challenged by the fact that motional states of trapped ions have been observed to decohere anomalously rapidly, as 1=d4, for ionsurface distances d, and also by the observation that light on dielectric surfaces near trapped ions can cause charging and disruption of the trap equilibrium. Much closer positioning of ions to mirrors is desirable in, e.g., CQED systems where the ioncavity coupling strengths are inversely proportional to the cavity length, which scales approximately as d. Moreover, accurate positioning of the ion relative to the cavity mode is essential, and it is clear that traditional bulk assembly techniques will not scale well to the systems envisioned for trapped ion quantum computation.

We report on the demonstration of direct and scalable integration of an ion trap with a high reflectivity mirror, through microfabrication of a surface electrode ion trap on the mirror. A circular aperture in the central electrode, located 169 m underneath the trap center, allows the mirror to collect fluorescence and to image a single atomic ion. Despite its proximity, the presence of the mirror does not significantly perturb the trap, which is supported by the observation that trapping is stable with laser-cooled ion lifetimes of several hours and with minimal sensitivity to light-induced charging. Furthermore, operation of the trap at 15 K helps to suppress anomalous ion heating. This approach to integration of mirrors, and optics in general, in ion traps is scalable to a large number of ion traps, as multiple trapping zones with mirror apertures may be defined on the same substrate with no additional overhead for fabrication.

3. Ion traps can be integrated with optical fibers using a point-Paul trap geometry, with multi-RF excitation applied to allow sub-micrometer control over ion heigh and lateral position.

   Publication: Tony Hyun Kim, Peter F. Herskind, and Isaac L. Chuang Surface-electrode ion trap with integrated light source Appl. Phys. Lett. 98, 214103 (2011) [KHC11]



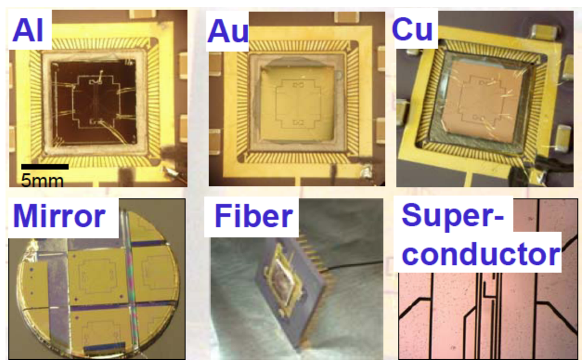
An array of trapped ions in optical cavities, connected by a network of optical fibers, represents a possible distributed architecture for large-scale quantum information processing. Due to the necessity of efficient light collection, laser cooling and qubit state manipulation, the realization of a quantum network or processor at the level of tens and hundreds of qubits strongly motivates the integration of optics in surface-electrode ion traps. However, the potential benefits of integrated optics have long been overshadowed by the challenge of trapping ions in the proximity of dielectrics, as well as the difficulty of guaranteeing good spatial overlap of the trapped ion with the field mode of the integrated element.

In the past, there have been demonstrations of integration of bulk mirrors, multimode (MM) optical fibers, and phase-Fresnel lenses into radio frequency (rf) traps with three-dimensional electrodes. More recently, integration of MM fibers and microscopic reflective optics for collection of ion fluorescence has been demonstrated in microfabricated surface-electrode traps. Complementing such efforts on light collection, the present work demonstrates light delivery through an integrated single-mode (SM) fiber in a scalable, surface-electrode design, and an in situ micrometer-scale positioning of the ion relative to the integrated structure. Future developments in optics integration, such as microcavities for the realization of quantum light-matter interfaces or lensed fibers for faster gate times and optical trapping of ions, will employ sub-10μm waists, underscoring the importance of in situ ion positioning.

We report on the construction of a fiber-trap system, and demonstrate the ability of the integrated light source to drive the 674 nm quadrupole transition of 88Sr+. The 674 nm transition is of particular interest in QIP with trapped ions, where it serves as the optical qubit, as well as in metrology, where it constitutes an optical frequency standard. The ion-fiber spatial overlap is optimized in situ by micromotion-free translation of the ion using segmented rf electrodes. We use this technique to map out the Gaussian profile of the fiber mode along a single transverse axis. With the ion over the center of the mode, we quantify the magnitude and timescale of fiber-induced charging.

4. Ion heating rates can be as low as 1 quanta/second, above Nb and Au surfaces, when operated at 6K, with an ion height of 100 μm. Nickel and silver traps saw higher heating rates, of about 20 quanta/sec, under similar operating conditions. Above the mirror surface, the best heating rate observed was 110 quanta/sec (at 150 μm height).

   Publications: [PhD Thesis] David Leibrandt (2009) Integrated chips and optical cavities for trapped ion quantum information processing; [PhD Thesis] Jaroslaw Labaziewicz (2008) High Fidelity Quantum Gates with Ions in Cryogenic Microfabricated Ion Traps; [PhD Thesis] Shannon Wang (2012) Quantum Gates, Sensors, and Systems with Trapped Ions.



MIT: Summary of Traps Tested

As of August, 2010:

Trap	# traps	Ion Height	Heating Rate & Observations
Ag	12	75-200μm	20 q/sec min
Au	11	75-100μm	2 q/sec min: CM 183 q/sec, BR 32 q/sec
NbN	2	100μm	12 q/sec min; Non-conducting above T_c
Nb	14	100μm; 600μm	<1 q/sec min ; still low heating after ~1.5 years
Al	9	75 & 100μm	7 q/sec min
Cu	3	100μm; 600μm	68 q/sec min (100μm trap)
Ni	1	75μm	19 q/sec ; electroplated
Mirror	4	150μm	108 q/sec
Point Paul	6	200 to 1100μm	Heating rates not yet measured
SMIT-II	10	65μm	Ions trapped July 2010; ~40 q/sec min

Total: **72** traps (average 2.3 traps / month ; peak 10 traps / month)

5. Laser-induced trap charging is low (virtually negligible) in gold traps, about 20 $\times$ higher in copper traps, and about 100 $\times$ higher in Aluminum traps, for typical wavelengths used in trapping Sr^+.

   Publication: Shannon X. Wang, Guang Hao Low, Nathan S. Lachenmyer, Yufei Ge, Peter F. Herskind, and Isaac L. Chuang Laser-induced charging of microfabricated ion traps J. Appl. Phys. 110, 104901 (2011)[WLL+11]

   Microfabricated ion traps are promising candidates for realizing large-scale quantum computers. Recent efforts have concentrated on development of multi-zone surface-electrode ion traps with small trap sizes, so that traditional microfabrication techniques can be employed. The typical ion-to-metal distance in these traps is on the order of 10100 m, small enough that the trapped ions are sensitive to surface effects such as electric-field noise (causing anomalous heating) and localized charging of the trap electrodes or substrate. While anomalous heating of ions trapped in microfabricated traps has been studied extensively both by theory and experiment, laser-induced charging has only seen a few systematic experiments recently. So far, laser-induced charging has been studied on the glass substrate of planar gold traps, on copper traps including insulators brought closer to the trap surface, and aluminum traps. Several unknown issues, including material dependence and the role of oxide layers on the metal, remain. For example, no such studies of charging have been done on aluminum traps with varying oxide layers, or comparisons made between different electrode materials with the same experimental setup.

The lasers used for any typical ion trap experiment span a wide range of wavelengths. In a microfabricated trap, they are much closer to the trap surface, and as traps become smaller in size, it is increasingly difficult to avoid scatter caused by lasers illuminating the trap. In some experiments, lasers are deliberately shone onto the trap for the purpose of micromotion compensation. This could be expected to cause buildup of electrical charges on the trap surface due to the photoelectric effect. The typical shortest wavelengths needed for ion traps range from 194 nm for Hg+ to 493 nm for Ba+, corresponding to 6.4-2.5 eV. Typical work functions for metals used for ion traps such as Au, Ag, Al, Cu, etc are 4 eV or higher, but may change due to surface effects such as the presence of an oxide layer.

The choice of material for ion traps is an important consideration. Gold has been a popular choice due to its chemical inertness, and it has a high work function of greater than 5 eV, but is incompatible with traditional CMOS fabrication. Consequently there has been some interest in using aluminum2 or copper for microfabricated ion traps, which can take advantage of sophisticated CMOS fabrication techniques. Pure aluminum has a high work function at 4.2 eV and is expected not to release electrons when illuminated with light at 405 nm for Sr+. However, aluminum is also known to quickly form a native oxide layer, Al2O3, which may lower the work function and thus make it susceptible to blue light. Such effects have been observed in previous studies of the photoelectrochemical effects of blue light on aluminum and other materials. Local charges formed on the Al2O3 may not dissipate, changing the trapping potential and leading to excess micromotion, which can affect the stability of the trap.

In this work, we study the charging behavior of aluminum, copper, and gold microfabricated traps when illuminated with lasers at 674, 460, 405, and 370 nm. All traps are operated in a cryogenic system at 6 K. Charging is measured by observing the micromotion amplitude of a single trapped 88Sr+ ion and relating it to ion displacement. In the aluminum traps, we find a wavelength dependence of the charging behavior: the laser at 405 nm charges the trap noticeably on timescales of minutes, whereas minimal charging is observed with 460 nm and 674 nm lasers over the same timescales. Copper traps exhibit charging at all wavelengths. No charging is observed at any of these wavelengths for gold traps, but some is observed at 370 nm.

2.1 References

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2.2 Appendices

None.